



**Search for the Standard-Model Higgs Boson in the Decay Channel of
 $H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$, $\ell = \{e, \mu\}$, with 184 pb^{-1} of Run II Data at CDF**

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Standard Model Higgs production and decay in the channel $p\bar{p} \rightarrow H \rightarrow WW \rightarrow \ell\nu\ell\nu$ where $\ell = \{e, \mu\}$, has been searched for at the $\sqrt{s} = 1.96 \text{ TeV}$ TeVatron collider using 184 pb^{-1} of Run 2 data collected by the CDF experiment. Observing no signal excess, we set a production cross section upper limit as a function of the Higgs mass M_H . We employ the fact that the azimuthal angle between the final-state leptons $\Delta\phi_{\ell\ell}$ is predicted to be smaller on average for scalar Higgs boson decays than for background processes. For $M_H = \{140, 150, 160, 170, 180\} \text{ GeV}$, we get a 95% C.L. limit of $\sigma \cdot \text{BR}_{\text{SM}}(p\bar{p} \rightarrow H \rightarrow WW) < \{17.8, 9.4, 5.6, 5.6, 6.4\} \text{ pb}$.

Preliminary Results for Summer 2004 Conferences

I. INTRODUCTION

In the Standard Model (SM) and its supersymmetric (SUSY) extensions, the Higgs boson is crucial to our understanding of electroweak symmetry breaking dynamics and the mass generation of electroweak gauge bosons and fermions. The Higgs boson mass is in addition an indicator of the scale of new physics. Electroweak precision measurements and LEP direct searches have constrained the Higgs mass to be within 114.4 and 251.1 GeV [1]. However, while all the high energy particle physics phenomena observed so far have been successfully explained by the Standard Model, the Higgs boson remains un-observed. It is the last missing piece and the most important one.

At the TeVatron the dominant SM Higgs boson production mechanism is gluon-gluon fusion, $gg \rightarrow H$. For a low mass Higgs decaying to $b\bar{b}$, Higgs bosons produced in this way are impossible to distinguish from jet-faked background, and the smaller cross-section associated production processes must be used for searches. On the other hand, when the mass of Higgs boson is greater than 136 GeV, the predominant mode of Higgs decay is to a pair of W bosons. Each of the W 's can further decay into either lepton plus neutrino or jets; the case of both W 's decaying leptonically is the most tractable experimentally due to the lower backgrounds. See figure 1.

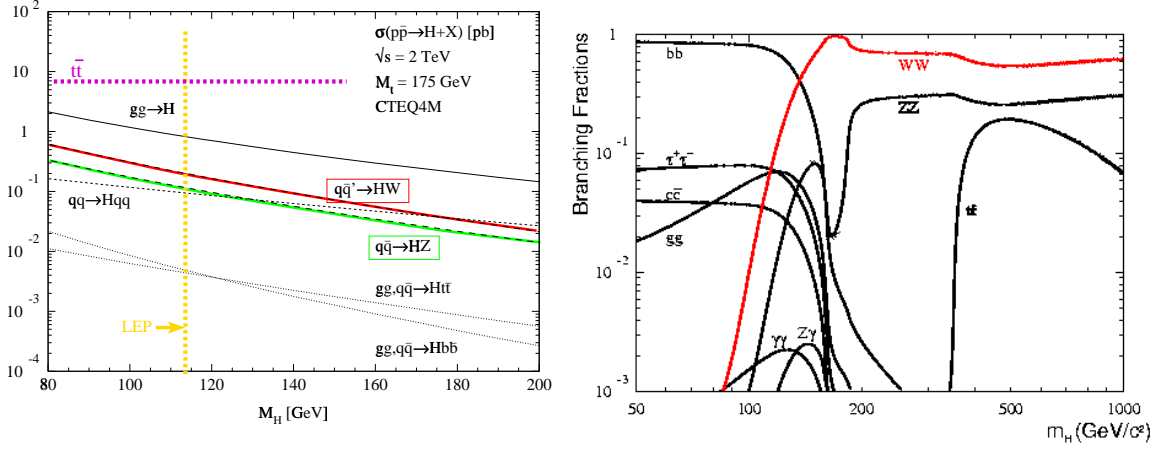


FIG. 1: The cross-sections of various SM Higgs production mechanisms at TeVatron and the branching ratios of various SM Higgs decay modes as a function of the Higgs mass [3].

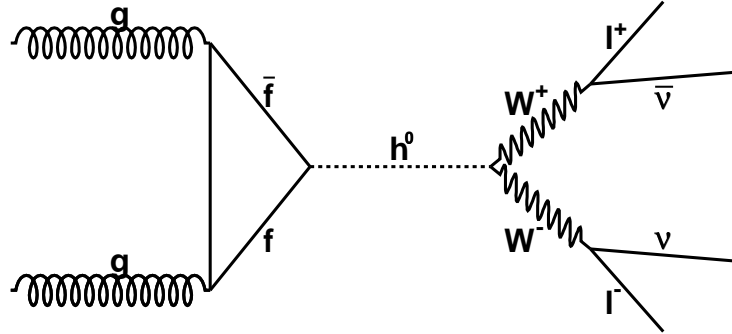


FIG. 2: Feynman diagram for SM Higgs production at the TeVatron, $gg \rightarrow H$, combined with the major Higgs decay channel at high Higgs mass, $H \rightarrow WW$, and further combined with the jet-free WW dilepton decay channel $WW \rightarrow \ell\nu\ell\nu$.

We report in this note the result of our search in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV for the signal of a high-mass SM Higgs boson that decays to a W pair and further to two leptons (electron and muon only) plus neutrinos. The dominant leading-order Feynman diagram for Higgs production and decay in this mode is shown in figure 2.

II. DATA SAMPLE AND EVENT SELECTION

The search is based on 184 pb^{-1} of TeVatron Run II data recorded by the Collider Detector at Fermilab (CDF) from March 2002 to September 2003. The CDF detector is described in detail in [4]. The central outer tracker (COT) is a precision drift chamber providing up to 96 spacial measurements for a track falling in its fiducial range $|\eta| < 1$ in a 1.4 T magnetic field. The silicon vertex detector (SVX) provides precise tracking close to the interaction point, especially important as a stand-alone tracker in the forward region. The electromagnetic (*em*) and hadronic (*had*) calorimeters provide energy measurements within $|\eta| < 3.6$. The muon chambers measure muon tracks within $|\eta| < 1$.

The data are collected with inclusive high- p_t lepton triggers (one of the following):

1. a central *em* cluster with transverse energy $E_t > 18 \text{ GeV}$ and transverse momentum $p_t > 9 \text{ GeV}$
2. a central muon track with $p_t > 18 \text{ GeV}$
3. a forward *em* cluster with $E_t > 20 \text{ GeV}$ and missing transverse energy $\cancel{E}_t > 15 \text{ GeV}$ where $\cancel{E}_t \equiv$ the negative vector sum of the transverse energies measured in *em* and *had* calorimeters.

Electrons are identified on the basis of their electromagnetic showers. To select a central electron we require an isolated *em* cluster in the central calorimetric region with $E_t > 20 \text{ GeV}$, matched to an isolated COT track with $p_t > 10 \text{ GeV}$ and $E_t/p_t < 2$ (or a cluster with $E_t > 100 \text{ GeV}$, matched to a COT track with $p_t > 50 \text{ GeV}$). To select a forward electron we require an isolated *em* cluster in the forward calorimetric region (within $1.2 < |\eta| < 2$ for good tracking quality) with $E_t > 20 \text{ GeV}$, matched to a SVX track [5]. Both central and forward electrons are required the following. The cluster must have small fraction of energy deposit in the hadronic calorimeters: $E_{had}/E_{em}^{\text{central}} < 0.055 + 0.00045E$; $E_{had}/E_{em}^{\text{forward}} < 0.05$ for $E_{em} \leq 100 \text{ GeV}$ and $0.05 + 0.026 \ln(E_{em}/100)$ for $E_{em} > 100 \text{ GeV}$. The cluster must have its shower profile consistent with that measured in testbeam electron data. One may refer to [6] for further details of our lepton identification.

Muons are identified as minimum-ionizing particle (MIP) tracks that have $p_t > 20 \text{ GeV}$ and $E_{em} < 2 + \max(0, 0.0115(p - 100)) \text{ GeV}$ while $E_{had} < 6 + \max(0, 0.0280(p - 100)) \text{ GeV}$. We avoid cosmic-ray muons by using the COT timing capabilities to reject events with one track entering and another exiting the tracker as well as requiring the isolated COT track to come from close to the interaction point (within $0.2(0.02) \text{ cm}$ (if with SVX hits)).

For both electrons and muons the track must intersect the beamline in the r - z plane within $z_{r=0} < 60 \text{ cm}$ from the interaction point to ensure good calorimetric measurement.

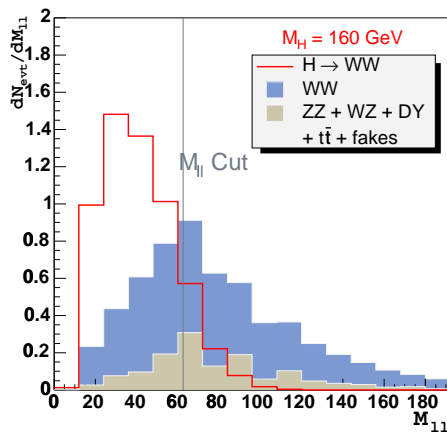


FIG. 3: Dilepton invariant mass distributions of signal ($M_H = 160 \text{ GeV}$), $WW \rightarrow \ell\nu\ell\nu$ background and the sum of other SM backgrounds as predicted by Monte Carlo (MC). The backgrounds are normalized to the expectation for 184 pb^{-1} and the signal normalized to the total background expectation. The dileptons from Higgs tend to have small $M_{\ell\ell}$ while those from other SM processes extend to high $M_{\ell\ell}$.

To select $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ events we require exactly two leptons with opposite charge signs found in one event. We require large missing transverse energy $\cancel{E}_t > 25 \text{ GeV}$ as evidence for the neutrinos. We require large azimuthal angular separation between small \cancel{E}_t and any lepton or jet, $\Delta\phi(\cancel{E}_t, \ell/j) > 20^\circ$ for $\cancel{E}_t < 50 \text{ GeV}$, to lower $Z \rightarrow \tau\tau$ background. We veto all the jets with $E_t > 15 \text{ GeV}$ and within $|\eta| < 2.5$. Jets are defined as localized energy deposits in the hadronic calorimeters and are reconstructed using an iterative clustering algorithm with a fixed cone radius of $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$. To lower $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ backgrounds we require large \cancel{E}_t significance for events

having dilepton invariant mass close to the Z -boson mass, $|M_{\ell\ell} - M_Z| < 15$ GeV. Further details of our event selection up to this point can be found in [7]. Finally we discriminate the Higgs signals from the WW background using the spin-zero property of the Higgs boson, which results in small invariant mass of the two leptons $M_{\ell\ell}$, figure 3, and azimuthal angular separation in between $\Delta\phi_{\ell\ell}$. We select events with small $M_{\ell\ell}$, table II, and use a binned maximum likelihood method on the $\Delta\phi_{\ell\ell}$ distribution to extract 95% C.L. signal production limit.

III. SIGNAL ACCEPTANCE

We have used PYTHIA 6.203 [8] to generate signal MC samples at $M_H = \{140, 150, 160, 170, 180\}$ GeV with CTEQ5L parton distribution functions. We simulate detector response to signals with the standard CDF detector simulation packages. The estimated signal acceptances for each Higgs mass are in table II.

IV. BACKGROUNDS

The backgrounds in our analysis include diboson (WW , WZ & ZZ), $t\bar{t}$, Drell-Yan (DY) $Z/\gamma^* \rightarrow \ell^+\ell^-$ where $\ell = \{e, \mu, \tau\}$ and $W + jet(s)$ events in which one jet fakes a lepton, with the dominant background being $WW \rightarrow \ell\nu\ell\nu$.

The diboson and DY backgrounds are estimated with PYTHIA [8] MC normalized to their SM cross-sections, $\sigma(p\bar{p} \rightarrow WW/WZ/ZZ) = 13.25/3.96/1.43$ pb and $\sigma_{\text{NNLO}} \cdot \text{BR}(p\bar{p} \rightarrow Z/\gamma^* \rightarrow \ell\ell; M_{\ell\ell} > 30 \text{ GeV}) = 236$ pb. The $t\bar{t}$ background is estimated with HERWIG [9] MC normalized to its SM cross-section, $\sigma(p\bar{p} \rightarrow t\bar{t}) = 7$ pb.

We estimate $W + jet$ background with data. With inclusive jet data, we calculate the probabilities for a jet to fake a lepton, which are defined as

$$R_e \equiv (\text{non-}W/Z \text{ electrons [10]; leading jets excluded}) / (\text{jets with } E_t > 20 \text{ GeV});$$

$$R_\mu \equiv (\text{non-}W/Z \text{ muons [10]}) / (\text{MIP-consistent tracks [11]}).$$

We search inclusive high- p_t lepton data for jets with raw $E_t > 20$ GeV or MIP-consistency that, together with another lepton-like object, pass the signal event selection. Applying the fake probabilities to such events gives the background of jet-fakes in the Higgs search results. Note that $R \sim 10^{-3}$ - 10^{-4} confirms the initial expectation that the background from $W + jet$ production dominates that from pure QCD processes such as dijet production.

The grand summary of signal and background expectations for the 184^{-1} analyzed data is given in table I. The $\Delta\phi_{\ell\ell}$ and $M_c \equiv \sqrt{p_{t\ell\ell}^2 + M_{\ell\ell}^2} + \cancel{E}_t$ distributions are shown in figure 4.

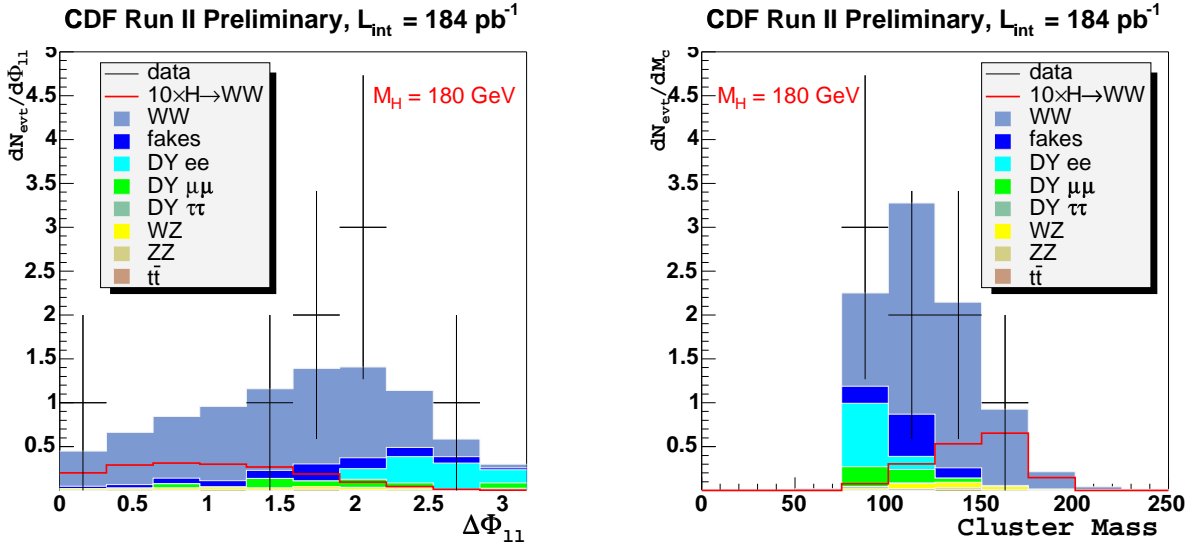


FIG. 4: The dilepton azimuthal angular separation $\Delta\phi_{\ell\ell}$ distribution (left) and the cluster mass M_c distribution (right) of data and MC signal and background expectations for $M_H = 180$ GeV.

M_H	140 GeV	150 GeV	160 GeV	170 GeV	180 GeV
DY ee	0.00 ± 0.00	0.15 ± 0.16	0.42 ± 0.28	0.72 ± 0.39	0.87 ± 0.44
DY $\mu\mu$	0.17 ± 0.11	0.17 ± 0.11	0.22 ± 0.12	0.32 ± 0.16	0.43 ± 0.19
DY $\tau\tau$	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.01	0.02 ± 0.01	0.03 ± 0.01
fakes	0.40 ± 0.12	0.45 ± 0.14	0.53 ± 0.16	0.65 ± 0.19	0.81 ± 0.25
$t\bar{t}$	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.01	0.02 ± 0.01
ZZ	0.02 ± 0.00	0.03 ± 0.00	0.03 ± 0.00	0.04 ± 0.00	0.06 ± 0.01
WZ	0.08 ± 0.01	0.10 ± 0.01	0.12 ± 0.01	0.15 ± 0.01	0.18 ± 0.02
WW	3.50 ± 0.41	3.82 ± 0.45	4.45 ± 0.52	5.38 ± 0.63	6.49 ± 0.76
tot bg	4.19 ± 0.45	4.22 ± 0.52	5.79 ± 0.64	7.29 ± 0.81	8.90 ± 0.98
signal	0.10 ± 0.01	0.16 ± 0.02	0.22 ± 0.03	0.22 ± 0.03	0.17 ± 0.02
data	2	2	3	7	8

TABLE I: Summary of signal and background expectations for 184 pb^{-1} and number of candidates observed in data for each Higgs mass, combining all the dilepton channels.

V. RESULTS

We use a binned maximum likelihood method on the $\Delta\phi_{\ell\ell}$ distribution of data and MC signal, WW and the sum of other SM backgrounds, figure 5, to set 95% C.L. upper limits on $\sigma \cdot \text{BR}_{\text{SM}}(p\bar{p} \rightarrow H \rightarrow WW)$ as a function of Higgs mass for $140 < M_H < 180 \text{ GeV}$. We compare the results to those obtained by using a simple counting method.

The simple counting experiment limits are obtained from the Poisson probabilities as a function of $\sigma \cdot \text{BR}(p\bar{p} \rightarrow H \rightarrow WW)$ for the data to equal the expected signal plus WW and the sum of other SM backgrounds (all appropriately smeared by their uncertainties).

The binned likelihood method uses the $\Delta\phi_{\ell\ell}$ distribution to obtain a likelihood function which is the product of Poisson probabilities (as defined above) in each bin. This likelihood function is then integrated over the assumed Gaussian uncertainties on the acceptance, backgrounds, and luminosity, and plotted as a function of $\sigma \cdot \text{BR}(p\bar{p} \rightarrow H \rightarrow WW)$. The 95% C.L. limit is then the value of $\sigma \cdot \text{BR}(gg \rightarrow H \rightarrow WW)$ corresponding to 95% of the area of the likelihood curve. Pseudoexperiments were done to obtain expected limits given the observations and to verify the likelihood behavior.

The results are summarized in table II, together with the input values.

VI. CONCLUSION

Standard Model Higgs production and decay at the Tevatron in the mode $p\bar{p} \rightarrow H \rightarrow WW \rightarrow \ell\nu\ell\nu$ where $\ell = \{e, \mu\}$ has been searched for in 184 pb^{-1} of Run II CDF data. No signal is seen and a 95% C.L. upper limit on $\sigma \cdot \text{BR}_{\text{SM}}(p\bar{p} \rightarrow H \rightarrow WW)$ at $\sqrt{s} = 1.96 \text{ TeV}$ has been set as a function of Higgs mass in the range 140 to 180 GeV. We look forward to improving this result with more data and a further optimised search.

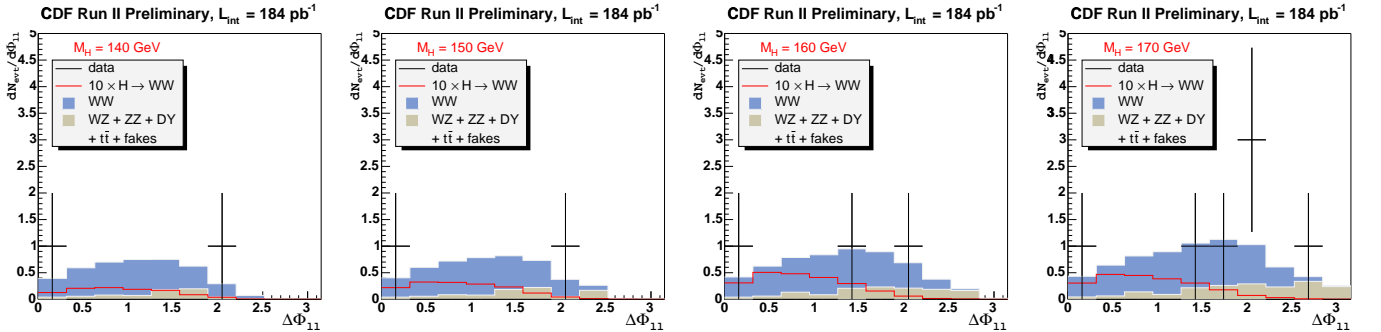


FIG. 5: The dilepton azimuthal angular separation $\Delta\phi_{\ell\ell}$ distribution of data and MC signal, WW and sum of other SM background expectations for $M_H = \{140, 150, 160, 170\} \text{ GeV}$.

Higgs mass M_H	140 GeV	150 GeV	160 GeV	170 GeV	180 GeV
$\sigma_{\text{SM}}(gg \rightarrow H)$	0.45 pb	0.36 pb	0.30 pb	0.25 pb	0.21 pb
$\text{BR}_{\text{SM}}(H \rightarrow WW)$	0.48	0.68	0.90	0.97	0.94
$M_{ll} <$	55.0 GeV	57.5 GeV	62.5 GeV	70.0 GeV	80.0 GeV
\mathcal{L}_{int}	$184 \pm 11 \text{ pb}^{-1}$				
$\epsilon_{\text{tot}} (\%)$	0.124 ± 0.012	0.228 ± 0.023	0.402 ± 0.040	0.476 ± 0.048	0.449 ± 0.045
expected signal	0.10 ± 0.01	0.15 ± 0.02	0.22 ± 0.03	0.22 ± 0.03	0.17 ± 0.02
WW background	3.51 ± 0.41	3.82 ± 0.45	4.45 ± 0.52	5.38 ± 0.63	6.49 ± 0.76
Σ other SM bg	0.68 ± 0.16	0.90 ± 0.24	1.34 ± 0.35	1.91 ± 0.47	2.40 ± 0.55
data candidates	2	2	3	7	8
limit—sim.counting	18.4 pb	9.8 pb	6.2 pb	8.2 pb	8.8 pb
expected limit— $\Delta\phi$	18.1 pb	9.8 pb	6.0 pb	7.4 pb	8.0 pb
limit— $\Delta\phi_{ll}$ -binned	17.8 pb	9.4 pb	5.6 pb	5.6 pb	6.4 pb

TABLE II: Inputs and 95% C.L. limits on $\sigma \cdot \text{BR}(gg \rightarrow H \rightarrow WW)$ at $\sqrt{s} = 1.96 \text{ TeV}$ for $140 < M_H < 180 \text{ GeV}$. The total acceptance ϵ_{tot} includes $\text{BR}(W \rightarrow \ell\nu)^2$.

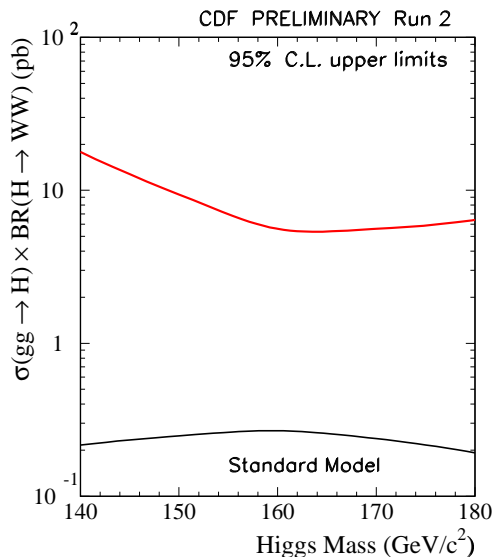


FIG. 6: CDF Run II 95% confidence level upper limits for $\sigma \cdot \text{BR}(gg \rightarrow H \rightarrow WW)$, in comparison with the Standard-Model prediction.

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- [10] electrons and muons from W decays are removed with the identification of one lepton and large \cancel{E}_t ; from Z decays are removed with the identification of two leptons having $M_{\ell\ell}$ inside the $M_Z \pm 15$ GeV window.
- [11] surviving all the muon cuts except on E_{em} and E_{had} .